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Soil moisture partitioning strategies in blowouts in the Hulunbeier grassland and response to rainfall

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Introduction: Soil moisture and soil water retention capacity are key influencing factors for the normal growth and development of vegetation. Understanding the dynamic change characteristics of soil moisture in blowouts and soil water retention capacity is of great significance for the management of blowouts.

Methods: This study employs drying and *in situ* monitoring methods to select typical blowouts in different regions (sand pits, fringe zones, sand accumulation zones, and sand-grass transition zones) on the Hulunbuir Grassland. A large area of natural grassland surrounding these regions was chosen as the control (CK). Soil moisture at depths of 20, 40, 60, 100 and 200 cm below the surface was measured along the soil profile using the ECH_2O-10HS soil moisture automatic monitoring instrument. The HOBO-RG3-M self-recording rain gauge was used to monitor rainfall. Soil water storage, coefficient of variation, and Pearson's correlation coefficient were calculated to study the differences in soil moisture and the dynamic change regularity in soil moisture under different rainfall conditions. This research provides important theoretical support for the soil moisture distribution and vegetation restoration in the blowouts of the Hulunbuir Grassland.

Results and discussion: The volumetric water content of the soil in the blowouts was 15.95%, the volumetric soil water content in different parts of the soil varied from low to high as follows: sand pit-I < sand-grass transition zone-IV < fringe zone-II < CK < sand accumulation zone-III. The soil volumetric water content of the 0–40 cm soil layer of the blowout was higher than 17.47%, and the soil volumetric water content of the 40–200 cm soil layer ranged from 12.13% to 17.47%. The volumetric water content of soil in various parts of the blowouts under different rainfall amounts had significant differences, with rainstorms and heavy rainfall effectively recharging the blowouts to a depth of 200 cm, and the blowouts responded strongly to heavy rainfall (71.5 mm). A gradual recovery of the pre-rainfall volumetric soil moisture content was seen approximately a week after rainstorms. The water retention and storage capacity of blowout soils was significantly higher than that of CK, the soil water storage capacity of different zones ranked in descending order as the sand accumulation zone (1875.38 mm) > edge zone (1373.22 mm) > CK (1188.36 mm) > sand pit (1000.39 mm) >

sand–grass transition zone (803.90 mm). The correlation coefficient of sand pits and sand cover was 0.5612, and that of sand accumulation zones and sand cover was 0.5845, which confirmed that sand cover enhanced the water retention capacity of the localized area of blowouts (sand accumulation zones).

KEYWORDS

soil volumetric water content, rainfall, soil water storage, blowouts, soil

1 Introduction

Grassland blowouts represent the beginning stage of the formation of grassland mobile dunes. As multiple adjacent blowouts develop, they overlap to form sand bands (Malakouti et al., 1978). The conversion of grassland landscapes to sandy landscapes occurs under the dual action of wind erosion and sand burial (Byrne, 1997). Blowouts form when wind erodes the surface of the grassland and sand accumulates and spreads on the downwind side of the pit under the action of the wind. This results in the "breaching" of the moisture in the grassland soil, which leads to blowouts and extremely dry soil on the downwind side of the soil surface. However, after the rainy season, the area of sand accumulation on the downwind side of the blowouts has the function of water storage. Therefore, studying the changes in soil water content in different parts of these blowouts under rainfall is of great significance to the investigation of the water conservation and storage capacity of such blowouts. Currently, related research on blowouts mainly focuses on their morphological classification (Deren, 2016; Deren et al., 2017; Gares and Nordstrom, 1995; Jungerius, 1984; Kejun et al., 2022; Yanguang et al., 2023; Zhang, 2007; Zhang, 2009; Zhang et al., 2006), mechanical composition (Ruru et al., 2019), airflow field (Ruru et al., 2019), erosion and accumulation characteristics, and influencing factors (Zhang et al., 2007a; Zhang et al., 2007b). Research on the distribution of soil moisture in blowouts and the response of blowouts to rainfall is of great significance to the in-depth understanding of the dynamic changes of soil moisture in blowouts and the water retention capacity of the soil for the management of blowouts. However, its investigation is relatively weak.

Soil water is an important component and key link in terrestrial ecosystems (Wang et al., 2019). Soil moisture dynamics are influenced by rainfall, runoff, evapotranspiration processes, and land-use practices (Luo, 2019). The recharge effect and transport process of soil water content may exhibit significant differences in different regions (Wei et al., 2022). Rainfall is the most important source of soil moisture recharge, and rainfall entering the surface soil water through the process of infiltration alters the original soil moisture distribution pattern, thus affecting the soil water storage capacity (Chen-Mao et al., 2022; Yinglan et al., 2018; Xinle et al., 2019). It is therefore important to study the response mechanism of soil moisture to rainfall. In recent years, many scholars have conducted research in this field. For example, by analyzing the graded response of soil water content to rainfall under different vegetation cover conditions, Chunheng et al. (2020) found that under the same precipitation conditions, the corresponding soil moisture varied greatly depending on the vegetation cover condition, and there was a precipitation threshold for initiating the soil water content response process. Daly and Porporato (2005) illustrated the relationship between rainfall and soil moisture using the Richards equation and the Green–Ampt model. Min et al. (2019) explored the seasonal variation rules and vertical distribution characteristics of soil water content in different land-use types in gently sloping windy and sandy areas of loess hills and found that the soil water content exhibited obvious vertical distribution characteristics. It has been shown that ground cover can insulate surface air, causing changes in surface soil properties that affect water transport (Qi, 2022). Juan (2020) explored the response of desert steppe soil moisture to precipitation and concluded that different classes of single precipitation had significant effects on the soil moisture content under different land cover types and that the timing of heavy precipitation dominated soil moisture, with a resonance relationship between time and soil moisture ranging from 5 to 8 months and 9–16 months. In the Maowusu sand land, precipitation of >8.8 mm can rehydrate the soil layer to a depth of 10 cm, and precipitation of >40 mm can infiltrate the soil layer to a depth of 110 cm (Guangyu et al., 2021). In their study of the response of moisture of the 0–200 cm soil layer to precipitation pulsation in the oil *Artemisia* scrub in the Kubuchi Desert, Bo et al. (2020) found that >8.6 mm rainfall recharged the soil layer to a depth of 30 cm and that 11.8 mm rainfall recharged the soil layer to a depth of 50 cm; the lag of feedback to precipitation was enhanced with the depth of the soil layer In summary, the response of soil moisture to rainfall varies under different vegetation cover conditions.

Blowouts are composed of two main parts: the depression sand pit and the sand material accumulation area. In their sub-part management research on blowouts, Na et al. (2020) proposed the combined use of sand barriers + plant sand fixation in blowout side slopes, edges, and sand accumulation areas. This combined approach increased the wind erosion pit slope vegetation coverage to 27.0%, and the number of plant species in the sand accumulation area reached six. Furthermore, the study of Qu et al. showed that in the rainy season, there was an artificial spread of poplar firewood and sand *Artemisia*, and a natural vegetation cover was formed in response to the integrated sand fixation technology. Thus, it is important to study the dynamic changes of soil moisture and rainfall response of blowouts for blowout management and vegetation restoration. In their study of the heterogeneous effect of soil moisture in wind erosion pits, Liman et al. (2022) showed that after the rainy season, the sand accumulation area of wind erosion pits had a certain "water storage" effect, while the sand pits and the edge area showed a serious "water loss" effect, and the soil was in an extremely dry state, creating conditions conducive for the expansion of wind erosion of sand pits. Wind erosion pits form large areas of quicksand, and the bare sand surface replaces the vegetation cover, which reduces the water loss by vegetation and surface

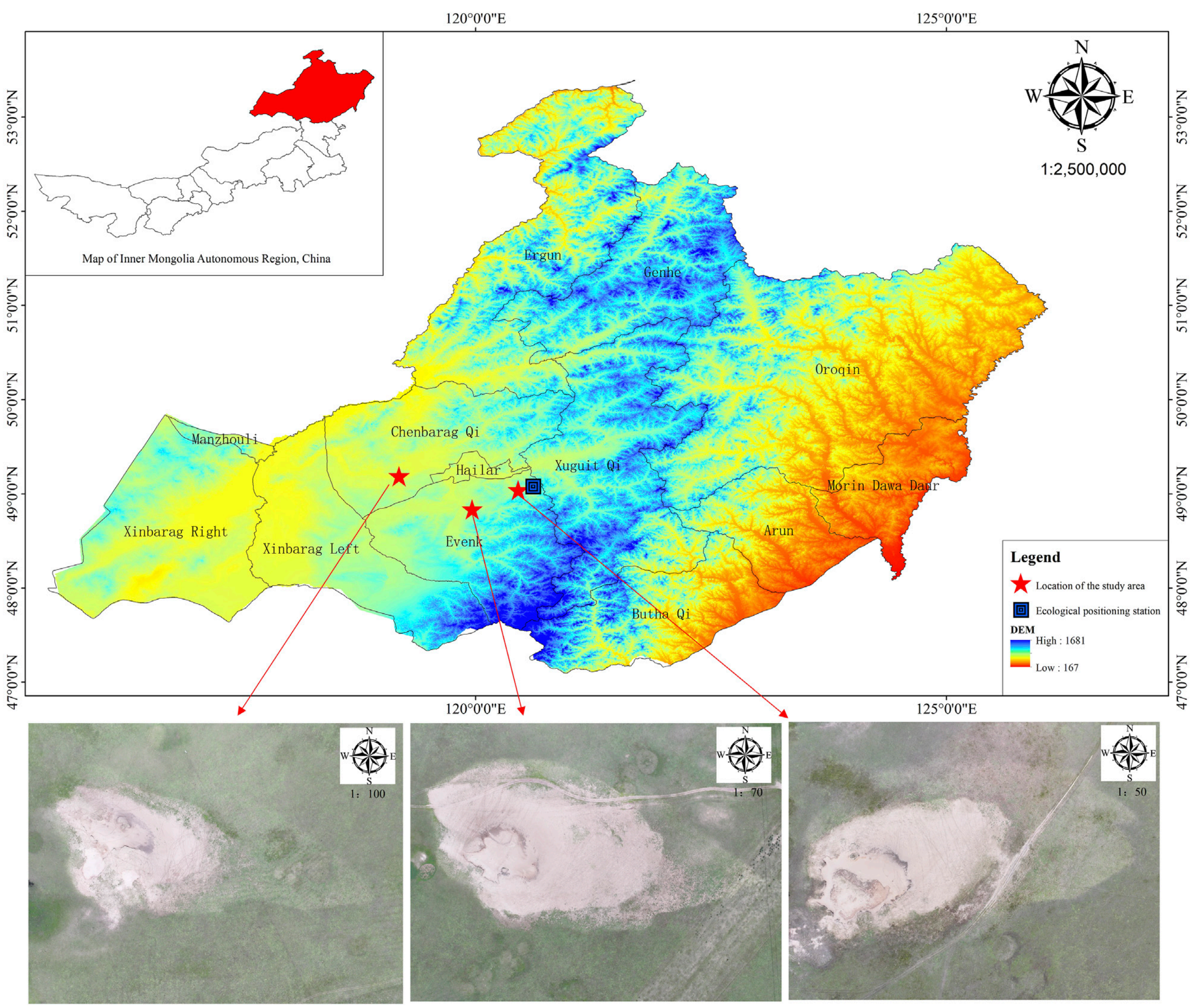

FIGURE 1
Study area location.

runoff, and the dry sand layer effectively locks the deep water. However, further studies are required to find out whether wind erosion pits have a positive effect on the deep water of the grassland under rainfall conditions. To clarify the distribution of the soil moisture content in blowouts and its response to rainfall, the present study selected four representative parts of the blowouts in the Hulunbeier grassland (sand pits, edge zones, sand accumulation zones, and sand–grass transition zones) as the research objects. Then, this study analyzed the dynamic changes of soil moisture in blowouts with natural grassland as the control (CK), compared the differences in soil moisture between different parts of the pits under different rainfall types, and clarified the response mechanism of blowouts to rainfall to determine whether wind pits have a water conservation benefit. This study aimed to (1) compare the differences in soil moisture in different parts of the blowouts under a variety of rainfall conditions; (2) understand the response mechanism of blowouts to rainfall; (3) explore whether blowouts provide the function of water retention; and (4) clarify the effect of blowouts on grassland soil moisture.

2 Material and methods

2.1 Study area

The study area is located in the Hulunbeier sandy grassland (Figure 1). The administrative area belongs to the territory of Ewenke Autonomous Banner, Hulunbeier City, Inner Mongolia Autonomous Region, in the center of the Hulunbeier grassland, south of the Daxing'anling Mountains, with an altitude of 691.10 m. The geographic coordinates of the study area are 120°45′30″–120°45′47″E, 49°03′67°–49°03′73″N. Ewenke Autonomous Banner has a temperate semi-arid continental climate, with dry and windy winters, mild and short summers, and precipitation concentrated in June–September. The average annual temperature ranges from −3.9°C to 1.2°C, and the average annual precipitation is 332.2 mm. The study area is located in the eastern part of Ewenke Autonomous Region, where black calcareous soil predominates, and the interior of the study area is dominated by sandy and windy soils, with residual

TABLE 1 Basic situation of blowouts.

Typical areas	Serial number	Sand thickness (cm)	Vegetation cover (%)	Soil water capacity (g·cm^{-3})	Total porosity (%)
Sand pit	I	80–84	0	1.61	32.51
Edge	II	0	40	1.60	35.01
Sand belt	III	40–50	3	1.61	31.48
Sand–grass transition zone	IV	6–10	50	1.61	34.11
CK	V	0	60	1.63	32.94

TABLE 2 Mechanical composition of blowouts.

Typical areas	Sand pit	Edge	Sand belt	Sand–grass transition zone	CK
Serial number	I	II	III	IV	V
Sticky particles/%	0.65 ± 0.08c	0.75 ± 0.05bc	0.75 ± 0.02bc	0.97 ± 0.01a	0.89 ± 0.23ab
Powdery grain/%	5.65 ± 0.73c	7.23 ± 0.75c	7.23 ± 0.37c	16.72 ± 1.77b	23.2 ± 3.78a
Very fine sand/%	0 ± 0b	0 ± 0b	0 ± 0b	0.18 ± 0.09a	1.37 ± 0.88b
Fine sand/%	21.1 ± 0.61a	16.55 ± 1.09bc	16.7 ± 0.51c	14.97 ± 0.47b	13.58 ± 1.43b
Medium sand/%	60.65 ± 0.33a	60.88 ± 0.45a	61.06 ± 0.39a	54.75 ± 1.3b	48.8 ± 2.16c
Coarse sand/%	12.04 ± 1.41b	14.58 ± 1.6a	13.99 ± 0.5ab	12.41 ± 0.36b	12.16 ± 0.69b
Very coarse sand/%	0 ± 0a	0 ± 0a	0 ± 0a	0 ± 0a	0 ± 0a

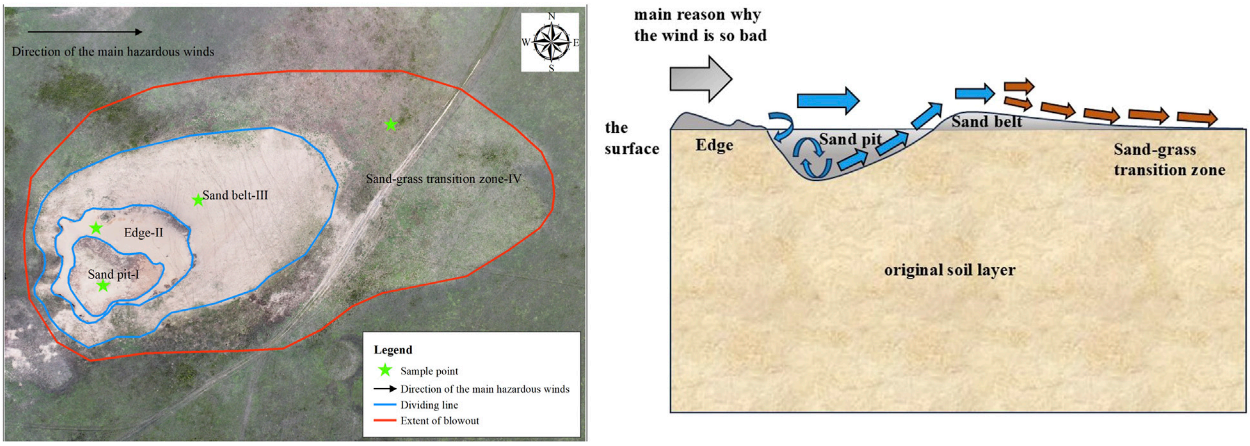

FIGURE 2
Schematic of blowout zoning.

black calcareous soils in some areas. The vegetation is dominated by thyme (*Thymus mongolicus*), stemless cinquefoil (*Potentilla acaulis*), the perennial grass *Cleistogenes squarrosa*, and needleleaf sedge (*Carex duriuscula* subsp. *rigescens*). Sand plants such as wolfsbane (*Stellera chamaejasme*) and fringed sagewort (*Artemisia frigida*) are scattered. The mechanical composition of soils in the area is dominated by medium and fine sands.

Natural grassland (CK) and blowouts in the study area were selected for investigation, the basic conditions of the blowouts were obtained using a field survey (Table 1), and the mechanical composition of the soil is shown in Table 2.

2.2 Sample plot selection and instrument setup

Blowouts are composed of two main parts: the depression sand pit and the sand material accumulation area (Shaoyun and Yuxing,

TABLE 3 Characteristics of different types of rainfall in the study area.

Type of rainfall	Rainfall criteria (mm)	Number of rainfall events	Proportion of total number of rainfall events (%)	Total rainfall (mm)	Proportion of total rainfall (%)
Light rain	0–10	20	60.61	43.50	16.00
Moderate rain	10–25	5	30.30	84.80	31.20
Heavy rain	25–50	2	6.06	72.00	26.49
Torrential rain	50–100	1	3.03	71.50	26.31
Total	0–100	28	100.00	271.80	100.00

2019). As a result, blowouts in the active stage of development can be divided into four typical parts, and the differentiation of each site is significant (Figure 2). According to the characteristics of each area of the investigated blowouts, the soil type, and the vegetation cover condition, the blowouts investigated in this study were divided into four typical parts from inside to outside: the sand pits (I), the edge zone (II), the sand accumulation zone (III), and the sand–grass transition zone (IV). The blowouts in the upwind direction and the natural grassland on the periphery were set as the control (CK). Using the drying method and *in situ* monitoring, the ECH$_2$O-10HS soil moisture automatic monitoring instrument was inserted horizontally along the soil profile to determine the volumetric moisture content and temperature of each soil layer in five sample plots at depths of 20 cm, 40 cm, 60 cm, 100 cm, and 200 cm from the surface in July 2023, with a monitoring frequency of 10 min. The HOBO-RG3-M type self-calculating rain gauge was installed in an open area of the study area to monitor the rainfall, with a data recording interval of 10 min and a measurement accuracy of 0.2 mm. Three blowouts were selected as replicates. The observation period was from 27 July 2023, to 25 September 2023, which was the plant growth period.

2.3 Rainfall characteristics

Rainfall with a large interval of at least 24 h was classified as a separate rainfall event (Ferrarezi et al., 2020). The 24-h rainfall was classified into five categories (Shengyuan, 2015): 0–10 mm was considered light rain; 10–25 mm was considered moderate rain; 25–50 mm was considered heavy rain; and 50–100 mm was considered torrential rain. From July 25 to 25 September 2023, a total of 28 rainfall events occurred in the study area (Table 3). The total rainfall was 271.80 mm, with a single-event minimum of 0.1 mm and a maximum of 71.50 mm. Light rain occurred 20 times, accounting for 60.61% of the total number of rainfall events, and contributed a total of 43.50 mm of the total rainfall, or 16%. Moderate rain occurred 5 times, accounting for 30.30% of the total number of rainfall events, with a total of 84.80 mm, or 31.20% of the total rainfall. Heavy rain occurred twice, accounting for 6.06% of the total number of rainfall events, contributing a total of 72.00 mm of precipitation, or 26.49% of the total. Torrential rainfall occurred the fewest number of times at only one heavy rainfall event, accounting for 3.03% of the total number of rainfall events and contributing 71.50 mm of precipitation, which accounted for 26.31% of the total rainfall. Rainfall data for the observation period (25 July 2023 to 25 September 2023) were obtained from the Hulunbeier Sand Observatory meteorological station near the study area.

2.4 Soil water storage

The amount of water stored in each layer of the soil, as well as the total amount of water stored, can be calculated using the following formula: (Wenfei et al., 2017)

$$SWS = SWC_i \times H_i \times 10$$

where SWS is the soil water storage capacity at the measurement depth (mm), SWC_i is the volumetric soil water content at the measurement depth (%), H_i is the thickness of the soil layer (cm), and 10 is the unit conversion factor (mm/cm).

2.5 Calculation of the coefficient of variation (CV)

The CV is a statistical measure of the degree of variability of each observation in the data, defined as the ratio of the sample standard deviation to the mean. In this paper, this index was used to examine the degree of variability of soil moisture between different months. CV < 10% was considered weak variability, 10% ≤ CV ≤ 100% was considered moderate variability, and CV > 100% was considered strong variability. The calculation formula is as follows: (Xueting et al., 2023)

$$CV = \left(\frac{SD}{MN}\right) \times 100\%,$$

where CV is the coefficient of variation (%), SD is the standard deviation, and MN is the mean.

2.6 Calculation of Pearson's correlation coefficient

Pearson's correlation coefficient was proposed by British statistician Pearson in the 20th century, and its formula is as follows: (Guozheng et al., 2023)

$$\rho = \left(\frac{COV(X,Y)}{\sqrt{D(X)}\sqrt{D(Y)}}\right)$$

where ρ is the correlation coefficient; COV(X,Y) is the covariance of variables X and Y; and D(X) and D(Y) are the variances of X and Y, respectively

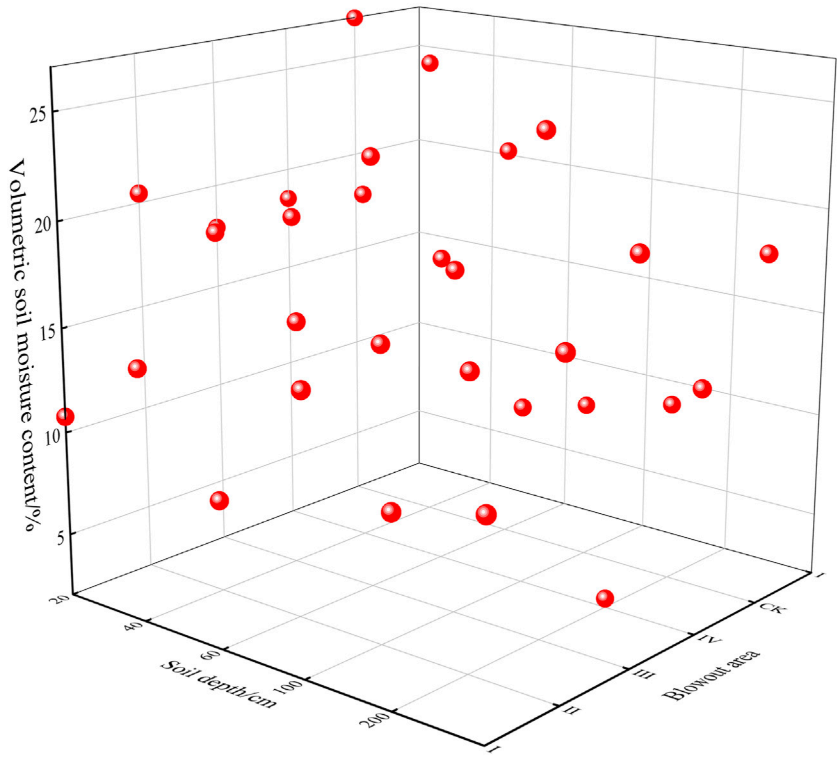

FIGURE 3
Volumetric water content of blowouts and CK soils.

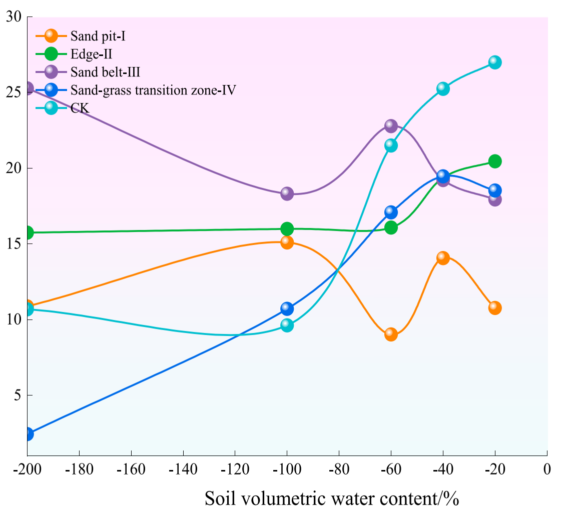

FIGURE 4
Soil volume water content in the vertical profiles of different parts of blowouts.

3 Results

3.1 Soil moisture heterogeneity in various parts of blowouts

Figure 3 displays the soil water content in the 0–200 cm soil layer in typical areas with blowouts. The soil volumetric water content did not differ significantly in different parts of the blowouts. The soil volumetric water contents in different parts of the pit were ranked from lowest to highest as follows: sand pit (I) < sand–grass transition zone (IV) < edge zone (II) < CK < sand accumulation zone (III). The soil volumetric water content of the sand accumulation zone (III) increased by 10.09% compared with CK, whereas the soil volumetric water contents of the sand pit (I), edge zone (II), and sand–grass transition zone (IV) decreased by 36.38%, 6.80%, and 27.45%, respectively, compared with CK. The mean value of the volumetric water content of blowout soil was 15.95%, which was decreased by 15.13% compared with CK.

With the deepening of the soil layer, the volumetric water content of the soil from 0 to 200 cm in different parts of the blowouts exhibited different degrees of changes (Figure 4). The soil volumetric water content of the sand pit (I) exhibited an M-shaped curve, with peaks of 14.06% and 15.09% at 40 cm and 100 cm, respectively, and the lowest volumetric water content at 60 cm, which was 9.02%. The volumetric water content of the edge zone (II) soil gradually decreased from shallow soil to deeper soil, declining from 20.44% to 15.74%. The volumetric water content of the sand accumulation zone (III) showed an N-shaped curve, with the lowest and highest values of 17.93% and 25.26%, respectively, found at 20 cm and 200 cm, respectively. The volumetric water content of the sand–grass transition zone (IV) gradually decreased below 40 cm, from 19.46% to 2.43%. The soil volumetric water content curve of the CK soil was similar to that of the sand–grass transition zone, but with similar curves found for all soil layers except for the soil at 100 cm, which contained much higher soil volumetric water content than the corresponding layer in the sand–grass transition zone (IV).

TABLE 4 Vertical profile of soil moisture variation in typical areas of blowouts.

Soil depth (cm)	Coefficient of variation (%)				
	Sand pit (zone I)	Edge (zone II)	Sand belt (zone III)	Sand–grass transition (zone IV)	CK
20	21.60	10.26	12.46	8.96	3.79
40	17.63	7.28	16.60	8.68	13.92
60	16.40	11.59	6.19	7.84	6.85
100	11.75	13.95	11.70	14.48	15.27
200	14.39	13.27	4.47	47.00	16.32
Average	16.35	11.27	10.28	17.39	11.23

As can be seen from Table 4, among the different soil layers in different parts of the blowouts, the CV was higher in the 20 cm layer of the sand pit (I) and the sand–grass transition zone (IV), which exhibited CV values of 21.60% and 47.00%, respectively. This result indicates that these two soil layers had a higher degree of dispersion and greater soil moisture fluctuation than the other layers. The soil volumetric water content of the sand pit (I) was moderately variable at all soil layers, and the degree of variability showed a decreasing trend with increasing depth. The soil volumetric water content at 40 cm in the blowout edge zone (II) was weakly variable, while the soil volumetric water contents of the remaining layers were moderately variable, and the degree of variation of the soil volumetric water content rose with the increase in soil depth from 40 cm downward. In the sand accumulation zone (III), the CV from 20 to 40 cm was moderate, the CV in the remaining layers was weak, and the highest CV was 16.60% at 40 cm. The sand–grass transition zone was weakly variable from 20 to 60 cm and moderately variable at 100 cm and 200 cm, but the soil layer at 200 cm had a higher CV, 47.00%, and was the soil layer with the highest CV among all parts of the blowout.

3.2 Response of soil moisture to rainfall in various parts of blowouts

The rainfall amount of 8.2 mm was analyzed as a representative light rainfall event, 15.7 mm was considered a representative moderate rainfall event, 45.3 mm was used as a representative heavy rainfall event, and 71.5 mm was considered a representative torrential rainfall event. Because the response time of each soil layer to rainfall differed, the maximum soil water content within 1 d after the end of rainfall was selected as the post-rainfall data.

The soil volumetric water content in different parts of the blowouts was significantly different under varying amounts of rainfall (Figure 5). The soil volumetric water content in different parts of the blowouts did not change significantly after receiving 8.2 mm of precipitation (Figure 5), and the rainfall only recharged to the 20 cm soil layer. The soil volumetric water content in zones I, II, III, and IV increased by 2.30%, 3.03%, 3.09%, and 2.67%, respectively, which were all higher than the corresponding increases in CK, and the soil layers below 20 cm did not display significant changes. This indicates that different parts of the blowouts below 20 cm did not exhibit a significant response to light rainfall events.

After 15.7 mm of rainfall, the soil volumetric water content of the soil layers at 0–40 cm changed significantly. At 20 cm, the soil volumetric water content of zones I, II, III, and IV increased by 1.85%, 6.44%, 3.51%, and 1.2%, respectively. At 40 cm, the soil volumetric water content of zones I, II, III, and IV increased by 0.91%, 0.95%, 0.51%, and 0.83%, respectively. At 60–200 cm, different parts of the blowouts were not significantly affected by rainfall, and the recharge was below 0.20%. These results indicate that different parts of the blowouts had a significant response to moderate rainfall from 0 to 40 cm.

After 45.3 mm of rainfall, the soil volumetric water content in different parts of the blowouts responded to different degrees. The soil volumetric water content at 200 cm in zones I, II, and IV responded strongly to rainfall, with increases of 4.40%, 8.70%, and 3.01%, respectively. Furthermore, the soil volumetric water content at 20 cm and 40 cm in the sand accumulation zone (III) exhibited a marked response to rainfall, with increases of 11.63% and 8.83%, respectively. The soil volumetric water content of the blowouts, except for the sand pit area, was recharged by rainfall by more than 13.58%. This was higher than the CK rainfall recharge, indicating that the soil of blowouts from 0 to 200 cm displayed a greater response to rainfall under heavy rainfall conditions and effectively recharged the soil layer at 200 cm.

After 71.5 mm of rainfall, the soil volumetric water content in different parts of the blowouts increased and exhibited a strong response. The response intensity of different parts of the blowouts from low to high was ranked as follows: CK (27.97%) < sand–grass transition zone (28.18%) < sand pit (34.75%) < sand accumulation zone (5.54%) < edge zone (42.81%). The soil layers in different parts of the blowouts were recharged by more than 3.00%, and the soil volumetric water content at 100 cm in zones I, II, III, and IV responded strongly to rainfall, with increases of 9.31%, 10.87%, 8.83%, and 9.59%, respectively, compared with the pre-rainfall period.

3.3 Effect of rainfall on soil water storage in blowouts

As can be seen from Figure 6, the soil volumetric water content of the blowouts can be roughly divided into three parts: the shallow soil layer at 0–40 cm, the medium-depth soil layer at 40–100 cm, and

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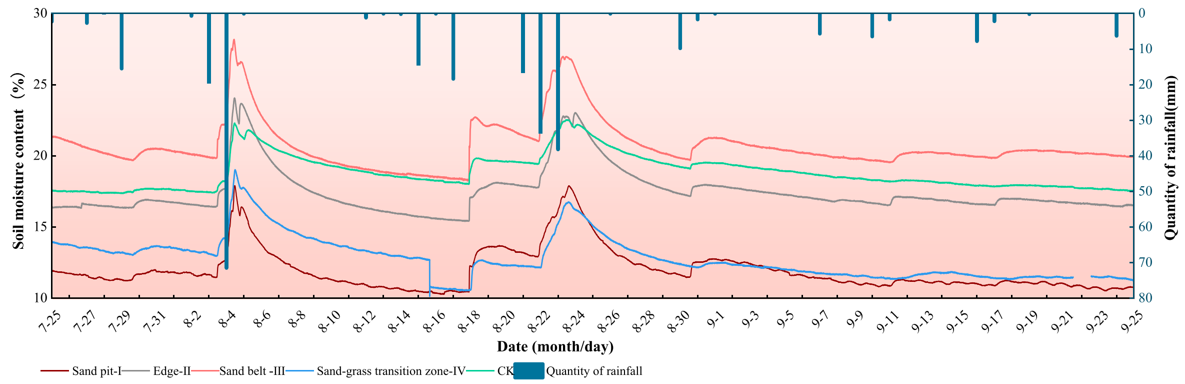

FIGURE 5
Dynamic changes of soil water content in different parts of blowouts.

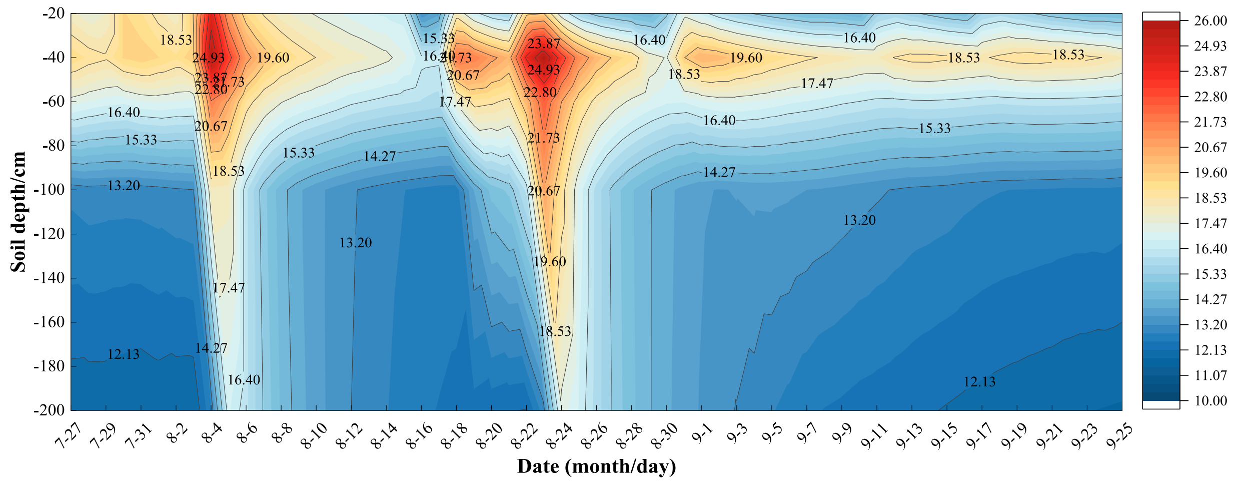

FIGURE 6
Dynamic contour plot of the soil volumetric water content of blowouts.

the deep soil layer from 100 to 200 cm. The volumetric water content of the soil at 0–40 cm was higher than that of other soil layers, with an average of more than 17.47%. The analysis of the response of the blowouts to rainfall indicated that the 0–40 cm soil layer displayed a stronger response to rainfall than the other soil layers and was easily recharged by water. This soil layer was recharged by light and moderate rainfall, but the volumetric water content of the soil decreased with time in the absence of rainfall. The volumetric water content of the soil in the middle-depth layer of 40–100 cm was 13.20%. The soil volumetric water content in the middle and deep soil layers from 40 to 100 cm ranged from 13.20% to 17.47%, which was increased by rainfall recharge and did not change significantly over time in the absence of rainfall recharge. The soil volumetric water content in the deep soil layers from 100 to 200 cm ranged from 12.13% to 15.55%.

Figure 7 depicts the dynamic changes of soil water storage in the 0–200 cm soil layer in different parts of the blowouts during the observation period. During the observation period, the cumulative rainfall was 278 mm. The soil water storage capacity in different parts of the blowouts showed fluctuations of different degrees, and the soil water storage capacity rose basically 1 d after the rainfall, which indicated that the absorption of rainfall exhibited hysteresis. As shown in Figure 7, the total soil water storage capacity of the blowouts was 1249.58 mm, which was 5.15% higher than that of CK. However, the water storage capacity of the blowouts was not as good as that of CK after sustained rainfall, water loss occurred more rapidly, and the overall total soil water storage capacity trend continued to decrease. Therefore, the soil water storage capacity of the blowouts was high, but their water retention and storage capacity was poor. Among the different parts of the blowouts, the soil water storage capacity ranked in descending order as zone III (1875.38 mm) > zone II (1373.22 mm) > CK (1188.36 mm) > zone I (1000.39 mm) > zone IV (803.90 mm). This result suggests that the water retention and storage capacity of the sand accumulation zone (III) is stronger than that of other zones, helping to preserve water, which may be because the surface layer of the sand accumulation zone (III) has a certain thickness, thereby enhancing the water retention and storage capacity of the sand accumulation zone.

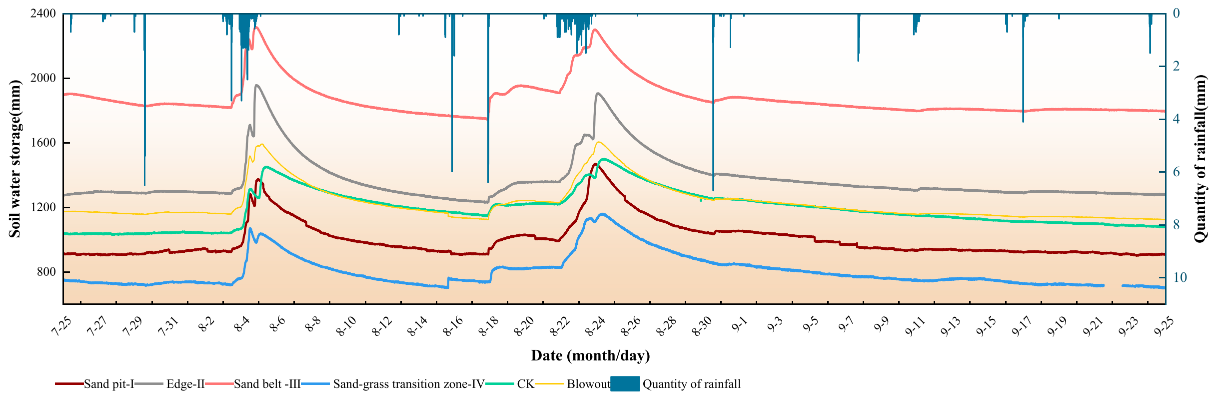

FIGURE 7
Dynamic changes of soil water storage in different parts of blowouts.

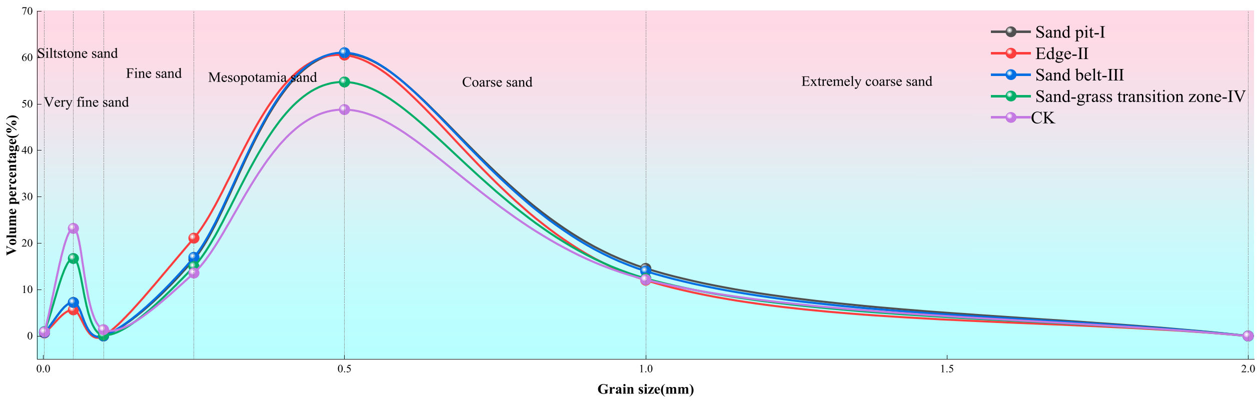

FIGURE 8
Soil particle size frequency distribution curve of wind-eroded crater soil.

4 Discussion

4.1 Influence of soil mechanical composition on soil moisture in blowouts

Soil moisture is closely related to the mechanical composition of the soil; the more loose and porous the soil, the lower the bulk density, and the more permeable the soil (Yun, 2013; Yanli, 2018). Xiwei (2018) investigated the evolution of sandy grassland blowout and suggested that the mechanical composition of blowout soils in the Hulunbeier sandy grassland is mostly dominated by fine sand, followed by medium sand. In contrast, the blowouts investigated in the present study were dominated by medium sand, followed by fine sand (Figure 8). This was consistent with Wang et al. (2008) conclusions regarding the mechanical composition of soils based on the study of trough-type blowouts in the Hulunbeier sandy grassland. Zhaungzhuang et al. (2020) suggested that soil macropores accelerate water infiltration and that soil macropores and rainfall intensity jointly influence the water infiltration process. Shenghua et al. (2019) conducted a study on the relationship between the soil water content and soil particle size distribution in desert grasslands and found that the soil water content was positively correlated with soil clay and fine particles. Honglian et al. (2022) and Honglian, 2022 research on the characteristics of deep soil moisture seepage in the Maowusu sandland suggested that soil texture is the main influencing factor affecting deep soil moisture seepage. In the present study, there was a linear fit between the soil moisture content and soil mechanical composition of blowouts, and the results indicated that the soil mechanical composition of different parts of the blowouts had different correlations to soil moisture. The correlations between soil moisture and clayey, powdery, very fine sand, and fine sand were positive, while the correlations between soil moisture and medium sand, coarse sand, and very coarse sand were negative.

4.2 Effect of sand cover thickness on the soil moisture content in blowouts

The dry sand layer has good permeability and can effectively recharge groundwater under heavy rainfall conditions (Dong et al., 2013). However, Jiansheng et al. (2014) suggested in their isotopic tracer study of moisture sources in the wet sand layer of the Alashan Desert that simulation experiments and natural rainfall observations

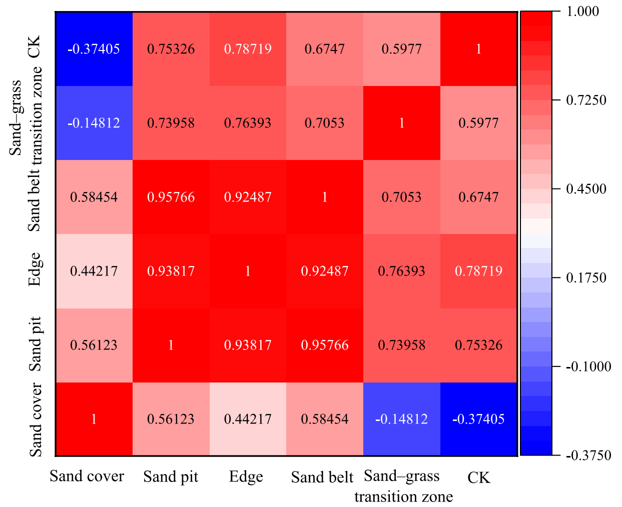

FIGURE 9
Correlation between the sand cover layer of blowouts and the soil water content of different soil layers.

indicated that rainfall could not effectively recharge groundwater. Precipitation first infiltrates the dry sand layer, where the infiltrated precipitation forms a thin film water layer. The water molecules continue to infiltrate deeper soil only when the content of the dry sand layer reaches its maximum water holding capacity. Because the dry sand layer is recharged by rainfall and the soil water content is close to the limiting value, the soil water is unlikely to infiltrate deeper layers substantially over time.

Different sand and wind processes, such as wind erosion and sand burial, occur in different parts of the blowout, and the thickness of the sand overburden layer varies from one part to another. Limin et al. (2022) investigated the heterogeneous effect of soil moisture in the blowouts in the Hulunbeier grassland and suggested that the soil moisture exhibited heterogeneity in five typical parts of blowouts. Based on further analyses, it was concluded that the sand-covered layer was effective in retaining the deeper layer of moisture. Therefore, in the present study, the correlation between the thickness of sand cover and the soil moisture in different parts of the blowouts was analyzed (Figure 9). The correlation coefficients between sand pits and sand cover and between sand accumulation zones and sand cover were 0.5612 and 0.5845, respectively, and the soil moisture content was higher in sand pits and sand accumulation zones with sand cover than in CK. This finding implies that the sand cover has a positive effect on the water retention capacity of localized areas of blowouts. Yinling et al. (2023) conducted a study on the relationship between soil moisture and topographic vegetation factors in fixed dunes at the southern edge of the Gurbantunggut Desert and found that the soil moisture at different depths showed a consistent unimodal distribution, with the order of soil moisture content in different soil layers being deep layer > middle layer > surface layer, exhibiting significant differences. In the present study, the soil moisture content of different soil layers in the blowouts was markedly different. This was probably because the blowouts evolved from grassland under the action of wind erosion and sand formation, which led to ecological disruption. The examination of the soil profile revealed that the thickness of the underlying black soil layer beneath the sand layer in different parts of the blowouts varied, leading to great differences in soil moisture.

4.3 Effect of rainfall on the water storage capacity of blowouts

Rainfall has a recharging effect on soil moisture, and the only source of moisture in desert areas is usually precipitation that infiltrates deep into the soil (Wenbin et al., 2014; XueYong et al., 2006). The deeper layers of dunes hold a large amount of water, but the surface soil moisture is low due to rapid evapotranspiration and wind erosion (Yuxing et al., 2020; Yun-zhu et al., 2021). However, the soil water content from 0 to 60 cm is more strongly affected by rainfall, making it more variable than other soil layers (Haiqin et al., 2020; Dongmei et al., 2005). In the present study, we examined the water retention and storage capacity of the blowouts and their different parts before and after rainfall. The results showed that the water storage capacity of the blowouts differed from that of the CK by 61.22 mm, and the overall soil moisture of the blowouts was higher than that of the CK. However, the water storage capacity of the blowouts was not as good as that of the CK after sustained rainfall, the loss of water was more rapid, and the overall soil moisture trend continued to decrease. As a result, blowout soils have a high water storage capacity but a poor water retention and storage capacity. The water retention and storage capacity of the sand accumulation zone was strong, which was consistent with the conclusion of the previous study (Xiwei et al., 2018).

5 Conclusion

This study investigated the response of soil moisture to rainfall in different parts of the blowouts in the Hulunbeier grassland and analyzed the changes in soil moisture in the pits. The main conclusions are as follows:

(1) The volumetric water content of the soil in different parts of the blowouts varied from low to high as follows: sand pit-I < sand-grass transition zone-IV < fringe zone-II < CK < sand accumulation zone-III. The soil volumetric water content in the 0–40 cm soil layer of the blowout was high, averaging more than 17.47%; the volumetric water content in the middle and deep soil layers at a depth of 40–100 cm ranged from 13.20% to 17.47%; and the volumetric water content in the soil layer at a depth of 100–200 cm ranged from 12.13% to 15.55%.

(2) The soil volumetric water content of the blowouts differed significantly under different rainfall amounts, and rainstorms effectively recharged the pits to a depth of 200 cm (i.e., the pits responded strongly to rainstorms). The volumetric water content of the soil gradually recovered approximately a week after the rainstorm.

(3) The water storage capacity of blowout soils was significantly higher than that of CK. The soil water storage capacity of different parts of the blowouts was in the order of sand accumulation zone (1875.38 mm) > edge zone

(1373.22 mm) > CK (1188.36 mm) > sand pit (1000.39 mm) > sand–grass transition zone (803.90 mm).

(4) The correlation analysis of the thickness of the sand cover layer and the soil moisture content in different parts of the blowouts demonstrated that the correlation coefficient of the sand pit and sand cover and that of the sand accumulation zone and sand cover layer were 0.5612 and 0.5845, respectively. In addition, the soil moisture content of the sand pit and sand accumulation zone was higher than that of the sand pit and sand accumulation zone in which the natural grassland had a sand cover layer, which indicated that the sand cover layer had a positive effect on the water retention capacity of the blowouts in the local area. However, in this study, we did not thoroughly investigate how much thickness is needed in the sand cover layer for it to have enough of a water retention effect to promote plant growth.

(5) The area of the blowouts investigated in this study was small, and blowout development occurs slowly; thus, the data did not represent all stages of blowout development. Therefore, in the follow-up study, the water storage capacity of different soil layers should be investigated in each blowout development stage (the bare sand, activation stage, fixation stage, extinction stage, and re-activation stage) to provide more rigorous theoretical support regarding whether blowouts have a positive effect on the soil moisture in grasslands.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZB: Writing–original draft, Writing–review and editing, Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration. LY: Project administration, Resources, Supervision, Writing–review and editing. ZM: Supervision, Writing–review and editing. EZ: Data curation, Methodology, Writing–original draft. LZ: Data curation, Writing–original draft. JL: Data curation, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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